

**UPPER LIMB REHABILITATION OF STROKE  
PATIENTS USING KINECT AND  
COMPUTER GAMES**

by

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## **ABSTRACT**

Stroke is a leading cause of death and adult disability in the United States. Survivors lose abilities that were controlled by the affected area of the brain. Rehabilitation therapy is administered to help survivors regain control of lost functional abilities. The number of sessions that stroke survivors attend are limited to the availability of a clinic close to their residence and the amount of time friends and family can devote to help them commute, as most are incapable of driving. Home-based therapy using virtual reality and computer games have the potential of solving these issues, increasing the amount of independent therapy performed by patients.

This thesis presents the design, development and testing of a low-cost system, potentially suitable for use in the home environment. This system is designed for rehabilitation of the impaired upper limb of stroke survivors. A Microsoft Kinect was used to track the position of the patient's hand and the game requires the user to move the arm over increasing large areas by sliding the arm on a support.

Studies were performed with six stroke survivors and five control subjects to determine the feasibility of the system. Patients played the game for 6 to 10 days and their game scores, range of motion and Fugl-Meyer scores were recorded for analysis. Statistically significant ( $p < 0.05$ ) differences were found

between the game scores of the first and last day of the study. Furthermore, acceptability surveys revealed patients enjoyed playing the game, found this kind of therapy more enjoyable than conventional therapy and were willing to use the system in the home environment. Future work in the system will be focused on larger studies, improving the comfort of patients while playing the game, and developing new games that address cognitive issues and integrate art and therapy.

To my family, my beloved girlfriend and all my friends and mentors who have supported me in this journey.

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# **CHAPTER 1**

## **INTRODUCTION**

Stroke occurs when blood flow to an area of the brain is interrupted when a blood clot blocks an artery or a blood vessel breaks [1]. This causes brain cells to die and brain damage occurs. Stroke is one of the leading causes of adult disability in the United States and the third leading cause of death [1]. Survivors lose abilities that were controlled by the affected area of the brain. Such abilities may include speech, memory and movement, among others, depending of the location of the affected area and the magnitude.

An effective rehabilitation allows most patients to regain enough movement and control of their limbs to perform their activities of daily living [2]. However, the number of sessions a patient attends and the intensity of them are resource-limited [3]. Another important aspect to consider is that therapy is often focused on walking, relegating upper limb rehabilitation to an afterthought [3].

Home based rehabilitation has the potential to provide stroke survivors the therapy they cannot afford to get in rehabilitation centers. It also has the advantages of a more familiar and private atmosphere. Recent developments in Virtual Reality and tracking devices offer tools to develop low cost rehabilitation systems suitable for home use [4-6].

## 1.1 Contributions of the thesis

A new system for home based rehabilitation of the upper limbs of stroke survivors was design and tested. A computer game was developed with the objective of making therapy sessions more enjoyable. Patients move their affected arm to control a cursor on a screen in order to play the game. Microsoft Kinect was used to track the user's hand and a Kalman filter was implemented to reduce noise from the data. This system fulfills the four features of a suitable game described by Burke, et al. [6] and three additional features that were included as requirements for a home-based system. After the study was done, the features considered during the design process were ranked to determine their importance. A physical therapist, the system's developer and a university professor involved in the study participated in the process. The final results, starting by the most important feature, are:

1. Right level of difficulty [6]
2. Direct feedback [6]
3. Easy to configure
4. Low cost
5. Minimal therapist involvement
6. Precise maneuvering [6]
7. Quick games [6]

The system designed constitutes an affordable and easy to use solution for in-home rehabilitation. The study showed a high acceptability of the system.

Participants were engaged with the game and enjoyed playing it. Furthermore, they all agreed they would use it at home.

This thesis has resulted in the following mechanical infrastructure that will be used for future studies of Kinect-based rehabilitation:

- Stand for the Kinect
- Hand support

Different locations for the Kinect with respect to the tracked hand were evaluated. The configuration that yields the best tracking and accuracy was determined to be when Kinect is located 28 inches above the hand support and pointing downwards. This distance keeps only the playing area inside the field of view of Kinect avoiding other moving object to interfere with the tracking of the hand. Having Kinect above the hand allows patients to calibrate and play the game while their arms are resting on the support. Furthermore, Kinect needs to be perpendicular to the hand support so the playing area is parallel to the tracker's xy plane.

The software written for this thesis can also be used as a framework for future work. Interaction between the computer and the Kinect was established and the tracked hand location was obtained in real world and projective coordinates. Furthermore, a Kalman filter was implemented and tuned to decrease data jitter (discussed in further detail in Chapter 4).

The software was written in C++ and PrimeSense [7] driver was used to interact with the Kinect. Open Natural Interface [8] (OpenNI) Middleware was

used for tracking and the graphical interface was handled with OpenGL [9]. Simple DirectMedia Layer (SDL) library [10] was used to upload images and the Kalman filter was implemented using the functions available in the Open Source Computer Vision (OpenCV) library [11].

## 1.2 Hypotheses

This thesis includes a human study to evaluate the game. The system presented was developed with the goal of fulfilling the features described in Section 1.1 and following recommendations of a physical therapist so the arm motion required to play the game is similar to those performed in therapy.

Conventional rehabilitation exercises can become tedious, providing little motivation to patients [6]. The inclusion of computer games should make therapy more enjoyable and since the game will require patients to move their arm in similar motions as therapy, similar results should be obtained. Therefore, the hypothesis studied in the human study is:

- Upper limb rehabilitation of stroke survivors, using computer games and Kinect, will:
  - maintain or improve patient's mobility, and
  - be more enjoyable than conventional therapy.

The hypothesis will be evaluated by comparing the patient's Fugl-Meyer upper extremity motor score obtained before and after the study. Patients will

also answer surveys before and after the study to assess the system's acceptability and whether they enjoyed the experience or not.

### 1.3 Outline of the thesis

The rest of the thesis is organized the following way:

Chapter 2 describes related work in the field of in-home rehabilitation. Previous works with Kinect are also described here.

Chapter 3 contains a paper submitted on March 29<sup>th</sup> to "The 34th Annual International Conference of the Engineering in Medicine and Biology Society". This paper is a feasibility study of the system and contains the results of a study performed with one stroke survivor.

Chapter 4 contains a paper submitted to the IEEE Transactions on Neural Systems and Rehabilitation Engineering. This paper discusses the characteristics of the system, the method employed in the study and the results obtained.

Chapter 5 discusses the conclusions and future work of this project.

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## **CHAPTER 2**

### **BACKGROUND**

Research on the use of Virtual Reality for rehabilitation of patients suffering from different conditions and disabilities has been going on for several years. Schönauer et al.[1] developed a serious game to help in the rehabilitation process of patients suffering chronic pain the neck and lower back. They track the patient's movements using Iotracker [2], a passive marker based motion capture system. Duff et al. [3] developed a mixed reality system for stroke rehabilitation. They used a motion capture system from the Motion Analysis Corporation [4] composed of 10 cameras and passive trackers. Both obtained promising results and are working on studies with larger groups.

Systems developed using motion capture devices have high accuracy but their high cost makes them inappropriate for home use. Other drawbacks of these approaches are the duration of the calibration process (4:25 min for [1]) and the need of placing markers in specific areas of the patient's body.

Using lower cost tracking devices greatly decreases the cost of a stroke rehabilitation system making it more affordable for home use. Several groups are working with camera based tracking. Burke et al. [5-7] created two small games focused on upper-limb rehabilitation. The camera tracks colored markers the

patient wears or holds with his hands. This research group has also studied the possibility of attaching the markers to real objects and tracking them instead of the patient's arms [5]. Geurts et al. [8] created various games that use webcam, Wii remotes and other tracking devices. They developed games targeting the rehabilitation of spasticity patients. An interesting system was developed by Burdea et al. [9] using infrared tracking. The patients wear a low friction forearm support that has some switches and the infrared LEDs.

Even though good results have been obtained by these groups there are some issues that limit or difficult the use of the systems at home. The patient's clothes can interfere with the tracking of passive color markers if similar colors are present. Changes in the room's lighting can also decrease the trackers accuracy or make it stop working. When active markers or Wii remotes are used the patient has to hold or wear a device. This can be troublesome and uncomfortable. Furthermore low functioning patients might not be able to grab the devices or open their hands to grip the trackers. Another disadvantage of using a single camera is that only 2D tracking is possible. This limits the rehabilitation exercises to just planar movements.

The commercially available Microsoft Kinect is a recently available low-cost tracking alternative. Schönauer et al. [1] compared the performance of this device with a Motion Capture system. They found Kinect cannot measure as many parameters and has a lower accuracy. However, they concluded that the game they developed for rehabilitation of chronic pain patients can be controlled

well with Kinect. Thus, this device can be used for home based rehabilitation as well.

Kinect has only been available for less than two years and few projects developed with it have been published. Hu et al. [10] used it to estimate the pose of the lower-limbs of a person using a wheeled walker. Lanari et al. [11] used inertial sensors combined with Kinect to estimate human motion. A Kalman filter combined the two measurements to improve the overall accuracy. Frati et al. [12] used this device to track a hand and improve position sensing of wearable haptic devices. Lange et al. [13] developed a game targeted to the rehabilitation of patients with balance issues. They used Kinect to track the upper body of the players. For the system to get calibrated, the patient has to stand about two meters away from Kinect with their arms up and stay still for a few seconds. This calibration method is not appropriate for stroke rehabilitation since most survivors are not able to go through this procedure. This tracking device can still be used with a different approach. Calibration would be much easier if only one hand is tracked at a time.

Home based rehabilitation can become a reality thanks to new and affordable technology such as Kinect. A system implemented with this device would have good tracking accuracy and would be very easy to use. The calibration process can be easy, especially for exercises directed to upper limb rehabilitation, where only the location of the hand would be tracked. The use of this device does not require any extra accessories, such as markers or hand

supports. A rehabilitation system using Kinect would also allow the design of exercises with 3D trajectories. No other low cost tracking device has these advantages and they should be exploited for in home rehabilitation and other applications.

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## **CHAPTER 3**

# **A FEASIBILITY STUDY OF AN UPPER LIMB REHABILITATION SYSTEM USING KINECT AND COMPUTER GAMES**

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## A Feasibility Study of an Upper Limb Rehabilitation System Using Kinect and Computer Games

Isaac Pastor, *Student Member, IEEE*, Heather A. Hayes, Stacy J. M. Bamberg, *Senior Member, IEEE*

**Abstract**— A new low-cost system for rehabilitation of the impaired upper limb for stroke survivors is presented. A computer game was developed specifically for this purpose and the user's impaired upper extremity is tracked using the Kinect, an inexpensive motion capture system commercially available from Microsoft. A Kalman filter was implemented to reduce data jittering. Patients are required to move their impaired arm, sliding it on top of a transparent support, in order to play the game. The game is personalized to the patient through specific settings that adapt to the patient's range of motion and motor control at the start of the game as well as performance during the game. The final score is proportional to the arm's movement speed. A feasibility study was carried out with one stroke survivor. The game was played for ten days and usability surveys were answered before and after the study. The patient was engaged with the game, found it easy to understand and reported willingness to use it in the home environment and enjoyment of the use in the clinic.

### I. INTRODUCTION

Stroke occurs when blood flow to an area of the brain is interrupted when a blood clot blocks an artery or a blood vessel breaks [1]. This causes brain cells to die and brain damage occurs. Stroke is one of the leading causes of adult disability in the United States and the third leading cause of death [1]. Stroke survivors may present with impaired speech, memory, and movement depending of the location of the affected area in the brain and the magnitude of the stroke. Ultimately goals of rehabilitation seek for stroke survivors to regain enough movement and control of their limbs to perform their activities of daily living [2]. However, the number of rehabilitation sessions a patient attends are limited and the goals may not be fully achieved, and in some cases rehabilitation is focused more on lower-limb rehabilitation to help subjects regain their walking abilities [3]. Additionally, the availability of transportation for the patient to get to the rehabilitation clinic, the amount of time and help their relatives and friends can provide to help in their commuting, economic situation and insurance policies can all limit a patient's rehabilitation. Thus, identification of novel modalities that allows continued focus on movement is imperative for continued improvement in the upper limb of stroke survivors.

Home based interventions have the potential to provide stroke survivors additional rehabilitation opportunities. It also has the advantages of a more familiar and private atmosphere and it eliminates the need to commute. Recent developments in Virtual Reality and tracking devices (e.g. a web cam with passive markers) offer novel tools at low cost, resulting in rehabilitation systems suitable for home use [4, 5].

Research on the use of Virtual Reality for rehabilitation has been ongoing for several years. Motion capture systems and serious games (e.g. games that are not for entertainment) have been proposed to help in the rehabilitation, for applications ranging from chronic pain [6] to stroke [7]. Even though these systems showed promising results, the high cost, the requirements of big spaces and the complexity of installing and setting up the tracking systems makes them inappropriate for rehabilitation outside of the clinical environment, for example in the home environment.

Lower cost tracking devices greatly decreases the overall price of such rehabilitation systems that are designed for use away from the clinic. For instance, several groups are working with webcams to track patient's hand or objects using passive markers [8-10]. The use of a camera and active markers, such as infrared LEDs has also been proposed [11]. The Nintendo Wii remote [12] is another inexpensive method of evaluating movement, and has been used for therapy [8]. Even though good results have been obtained by these groups there are some issues that limit the use of the systems at home or make implementation difficult away from a lab setting. The patient's clothes can interfere with the tracking of passive color markers if similar colors are present. Changes in the room's lighting can also decrease the trackers accuracy or make it stop working. Another disadvantage of using a single camera is that only 2D tracking is possible limiting rehabilitation exercises to just planar movements. In addition, when active markers or Wii remotes are used the patient has to hold or wear a device. This can be troublesome and uncomfortable. Furthermore, low functioning patients might not be able to grab the devices or open their hands to grip the trackers.

The commercially available Microsoft Kinect [13] is a recently available low-cost tracking alternative, and does not require users to hold or wear any specialized equipment for tracking. Its reasonably high accuracy (xy resolution = 3mm, z resolution 1 cm [14]) and low price makes it a good tracking alternative for a home based rehabilitation system. Schönauer *et al.* [6] compared the performance of this device with a Motion Capture system and found Kinect cannot measure as many parameters and has a lower accuracy. However, their study demonstrated a custom game that was nevertheless controlled well with Kinect [6].

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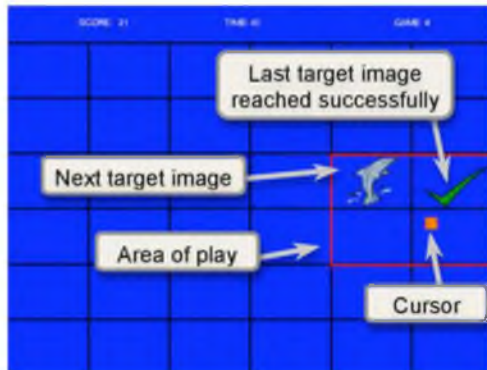
The Kinect has been commercially available for less than two years. A Kinect has been used to estimate the pose of the lower-limbs of a person using a wheeled walker [15] and to improve the measurements of inertial sensor [16] and wearable haptic devices [17]. A Kinect has also been used in rehabilitation, to track a patient's upper body in games targeted to treat balance issues [18]. However, for this particular system to be calibrated, the patient has to stand about two meters away from the Kinect with their arms up, and the patient must hold this position without moving for a few seconds. This calibration method is not appropriate for stroke rehabilitation since most survivors are not able to go through this procedure.

The Kinect is small and affordable, making it an excellent tool for use in home-based rehabilitation. In particular, when used at home a Kinect-based system can encourage increased use of the upper extremity for stroke survivors. The system presented here uses this device to track the patient's hand to play a game designed specifically for upper limb rehabilitation of stroke survivors. The calibration process is easy for a patient with a weak upper extremity and only requires the patients to move their hands in a waving motion on a flat surface at table height. Furthermore, no extra accessories, such as markers or hand supports, are required.

This paper presents a new system for the rehabilitation of the impaired upper limb of stroke survivors using computer games and Kinect. Section II describes the system proposed and the feasibility study. Sections III and IV contain the results and discussion, followed by conclusions in Section V.



(a)



(b)

Figure 1. (a) Illustration of the system's setup; (b) Screenshot of the game.

## II. METHOD

### A. Hardware setup

The system requires patients to sit in front of a table with a stand holding a Kinect, a hand support parallel to the table, and a monitor. The setup is shown in Figure 1(a). The software runs on a Dell Inspiron M501R Laptop connected to a 20" monitor. The game is shown on the monitor, and to play it, the patient moves the affected hand while resting on the support.

The arm support is needed because due to the patients' lack of strength and mobility of their impaired upper limb it can be difficult to keep their arms raised for extended periods of time. The easiest approach is for users to slide their arm on top of a table. It was found that Kinect has problems tracking the hand when it is in contact with an opaque surface. To solve this issue a transparent surface was placed parallel to the table and 15 cm above it. To maintain a comfortable height for the user's arm, a table with a lower height was used and the transparent hand support was placed on top. The Kinect was placed parallel to the table and about 70 cm above the hand's position, using a custom stand (as illustrated figuratively in Fig. 1a). This location gave the best results for tracking and accuracy.

### B. Software setup

1) *Interaction with Kinect:* Data was obtained using an open source driver made available by PrimeSense [19], the company who developed Kinect. Motion tracking middleware NITE, developed by Open Natural Interaction (OpenNI) [20], was used for tracking. NITE provided 3D coordinates of the tracked hand. These data were available as real world coordinates and as projective coordinates. To decrease jitter and noise, a Kalman filter was implemented.

2) *Game:* A game was designed and developed specifically for upper limb rehabilitation of stroke survivors. The game fulfills requirements developed in conjunction with the physical therapist team at the University of Utah's Rehabilitation and Wellness Clinic. Specifically, the objective of the game is to increase range of motion and decrease spasticity.

To meet this objective, the game requires the patients control a cursor on the screen by moving their hand. The goal of the game is to select images that randomly appear in any cell of a 6X6 grid. To select an image, patients need to locate the cursor inside the appropriate cell. Figure 1(b) shows an annotated screen shot of the game.

The game has a total of 10 rounds. For each round, the image randomly appears within different areas of the screen outlined in by a red rectangle (the "area of play"), as shown in Figure 1(b). This allows different portions of the range of motion to be targeted. The number of cells in the area of play increases gradually, making the game harder as it progresses. The size of the playing area is 2X2 for the first four games. Then, the size increases to 3X3 for games 5 and 6 and to 4X4 for games 7 and 8. The last two games are played on the entire screen (6X6). The first four games are played in bottom, left, top and right 2X2 areas of the screen, respectively (Figure 1(b) shows an area of play in the right

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2X2 area of the screen). Games 5 and 7 are played in the area where patients obtained the lowest score in the first four games. It is assumed that the lowest score corresponds to the area that requires the most effort and therefore additional targeted use by the patient. Games 6 and 8 are played in the opposite area of the screen so patients can rest from the previous workout.

Each round lasts between one and two minutes and there is a break of half the length of the round between them. Rounds are one minute long for the first two days of the study and their duration was periodically incremented every two days until they reached two minutes on the final days. To maintain the patient's interest the topic of the images shown changes every session. Household chores, transportation means, furniture are some of the topics that were used.

Before starting to play the game, users are asked to move their hand as far as they can to the left, right, away from and towards their body. These data is used to calibrate the range of motion required to play the game according to the user's abilities. The range of motion and the score of every round are stored for future analysis.

### C. Testing protocol

A preliminary study was implemented to evaluate the acceptance of the system and investigate the efficacy. The study was carried out with one stroke survivor. The patient played the game once a day for ten consecutive weekdays (Monday through Friday). Before the study began a pre-test was carried out in order to obtain patient's range of motion and teach the user how to play the game. Teaching the patient how to play the game before the study begins is aimed to decrease score improvement due to game learning. Patient's Fugl-Meyer upper extremity motor score was obtained before and after the study to determine if any improvement was achieved. The Fugl-Meyer is a stroke-specific, performance based impairment measure and provides information on motor recovery [21]. The patient also answered usability surveys before and after the study in order to analyze her expectations about and the acceptability of the system.

### D. Recruitment

A 46 year old female participated in the study. She suffered a stroke 25 months before the study began when a brain tumor was being removed. She stayed in the hospital for two months and has been doing therapy at the University of Utah Rehabilitation and Wellness Clinic, an outpatient exercise facility for stroke survivors, three times a week for 20 months. Her Fugl-Meyer upper extremity motor score was 16/66, indicating severe disability with hemiplegia.

## III. RESULTS

Figure 2 (a) and (b) show graphs of the patient's score and range of motion over the testing period. Day one corresponds to the pre-test and days two to eleven to the ten days of actual testing. Figure 2 (c) is a picture of the patient playing the game. The patient's Fugl-Meyer score remained at 16 (unchanged) after the study. Table 1 lists the survey questions and the pre- and post-test responses from the patient.

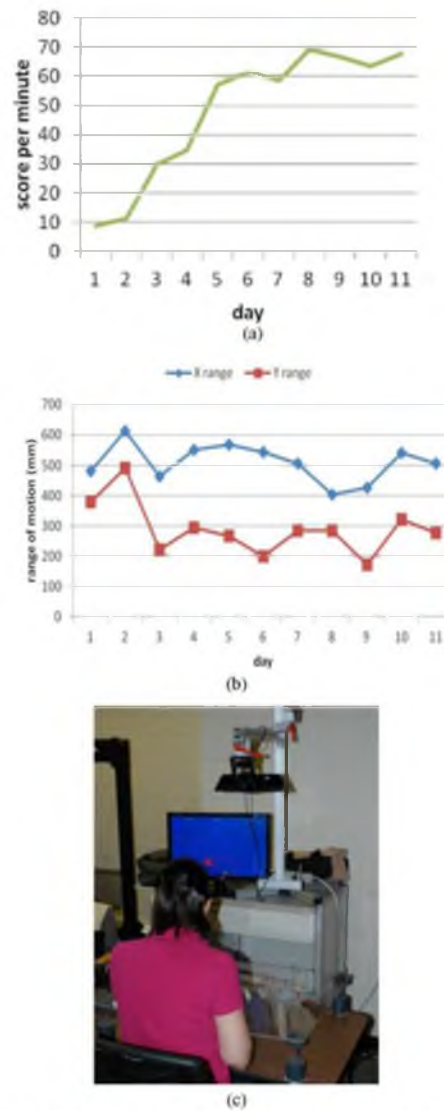


Figure 2. (a) Plot of score per minute versus days; (b) Plot of range of motion versus days; (c) Picture of patient playing the game

## IV. DISCUSSION

The patient attended all the sessions and was engaged with the game. She would remember the score obtained the previous day, and she tried to improve each day. The system's acceptability by the patient was high, as indicated by the scores in Table 1. Specifically, she found the game easy to understand, comfortable to play and she stated that she was willing to use the system at home. The use of the system over the two weeks period changed her perception of the game, as evidenced by her improvement on her rating of the statement, "Computer game based therapy is more enjoyable than classical therapy," from "strongly disagree" before the study to "agree" after it.



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TABLE I. SURVEY RESULTS

Survey Question	Pre-test	Post-test
Computer game based therapy can improve arm mobility	Strongly agree	Agree
Computer game based therapy is more enjoyable than classical therapy	Strongly disagree	Agree
It will be comfortable to play a computer game for therapy	Agree	Strongly Agree
The computer game for therapy will be easy to understand	Strongly Agree	Strongly Agree
I would be willing to use the system at home every day	N/A	Agree

The patient's game score increased throughout the study. The increase was bigger during the first week but there was also improvement during the second. The game's score is proportional to the arm's movement speed, and thus may be related to a decrease in spasticity. The range of motion did not change significantly throughout the study, however, nor did her Fugl Meyer score improve.

An unanticipated aspect was that the subject repeatedly helped move her impaired arm with her healthy arm. Although this may be an appropriate adaptive strategy, at this point, the main goal of the research is to evaluate whether this system can provide targeted rehabilitation to the impaired limb that results in improved performance. For the next study, we will recruit more patients, and will target those with more initial mobility (such that they do not feel a need to provide assistance with their healthy arm) by requiring a Fugl Meyer score above 33.

## V. CONCLUSION

The system developed provides a potential in-home novel rehabilitation system for stroke survivors. Its low-cost and easy-to-use characteristics makes it suitable for the home environment. In addition, the game is personalized to the patient's abilities each time it is played, by adapting to the range of motion and areas that are more difficult for the patient. In this initial study, the system's acceptability by the patient was high. The patient was engaged with the game and enjoyed the study. The game will now be implemented in a larger study with more subjects to further evaluate its efficacy and the interest levels of the subjects in having such a system available to them in the home environment.

## ACKNOWLEDGMENT

We are grateful to the study subject for her time, and to our colleagues in the Univ. of Utah Rehab. and Wellness Clinic, particularly David Miller, for their assistance in recruiting subjects and accommodating our study.

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## **CHAPTER 4**

# **UPPER LIMB REHABILITATION SYSTEM USING KINECT AND COMPUTER GAMES**

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the IEEE Transactions on Neural Systems and Rehabilitation Engineering.

# Upper Limb Rehabilitation System Using Kinect and Computer Games

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**Abstract**— A new low-cost system for rehabilitation of the impaired upper limb for stroke survivors was previously presented with data from an initial subject. This paper extends that work with evaluation results from an additional five stroke survivors and five control subjects. A computer game was developed specifically for upper limb rehabilitation, using the Kinect, an inexpensive motion capture system commercially available from Microsoft, to track the user's impaired upper limb, which is moved to score during the game. A Kalman filter was implemented to reduce data jittering. The game is personalized to the patient through specific settings that adapt to the patient's range of motion and motor control at the start of the game as well as performance during the game. The final score is proportional to the arm's movement speed. The game was played for six to ten days and usability surveys were answered before and after the study. Patients were engaged with the game, found it easy to understand and reported willingness to use it in the home environment and enjoyment of the use in the clinic. A significant change ( $p=0.018$ ) in game score was found over the duration of the study. Promising results were obtained and the system showed potential to be used in home-based therapy.

**Index Terms**— rehabilitation, low-cost, personalized health care.

## I. INTRODUCTION

**S**TROKE is the fourth leading cause of death in the United States and one of the leading causes of adult disability [1]. A stroke occurs when blood flow to an area of the brain is interrupted because a blood clot blocks an artery or a blood vessel breaks [1]. This causes brain cells to die and brain damage occurs. Stroke survivors lose abilities that were controlled by the affected area of the brain. Depending on the magnitude and the area where stroke occurs, speech, memory and movement can be affected. Most stroke survivors are able to regain enough control and movement of their arms and legs after an effective rehabilitation [2], allowing them to perform their activities of daily living. Unfortunately, not all patients can attend enough sessions and the intensity of the sessions is not always appropriate [3]. Finding transportation and someone to help with the commute to rehabilitation centers, along with insurance policies, economic situation and availability of nearby rehabilitation centers can all limit a patient's therapy. Furthermore, therapy at rehabilitation centers is often focused on walking, relegating upper limb rehabilitation to an afterthought [3].

In-home rehabilitation has the potential of addressing all the problems described above, thus providing stroke survivors the therapy they would otherwise not obtain. Therapy at home has the additional benefits of a more familiar and private

atmosphere and it eliminates the need to commute. Furthermore, therapy can be focused on the rehabilitation of areas overlooked in the clinic. Recent developments in Virtual Reality and tracking devices offer tools to develop low cost rehabilitation systems suitable for home use [4, 5].

An additional advantage of using Virtual Reality and games in rehabilitation is the high level of engagement created, leading to a better outcome [6]. Some rehabilitation exercises can be tedious; therefore patients don't feel motivated to do any independent therapy [7]. However, games have to be developed specifically for rehabilitation purposes. Off-the-shelf games require fine and coarse motion skills since they are targeted to people without any motor disabilities. Thus, rehabilitation patients typically do not have the skills required to play them [8].

The use of Virtual Reality in rehabilitation has been researched by several groups. Different systems have been developed and several approaches have been tested. High accuracy motion capture systems have been used for rehabilitation of chronic pain [9] and stroke [10]. Promising results have been obtained in these studies. These systems offer very good accuracy and a sensation of total immersion in the game. However, the requirement of a large space, the complexity of the installation and setting up of the tracking systems and their high cost makes these systems inappropriate for the home environment.

The use of lower cost tracking devices greatly decreases the overall price of the rehabilitation system. The use of passive markers and webcams is one of such approaches [7, 11, 12]. The use of video image based control system and a cyber glove is another approach used in rehabilitation systems [13]. Other groups are working with cameras and active markers, such as infrared LEDs [14]. The Nintendo Wii remote [15] and the Play Station EyeToy [16] are other inexpensive tracking devices whose use for therapy has been studied [12, 17-20]. Good results have been obtained by these groups but the systems have some issues that can limit their use outside the clinic environment. When passive markers are used, the color of the patient's clothing can interfere with tracking. Changes in the room's lighting can also decrease the trackers accuracy. The use of a single camera has the limitation of only being able to do 2D tracking, limiting rehabilitation exercises to just planar movements. Systems using active markers and the Wii remote require the user to hold or wear a device. This can be troublesome and uncomfortable. Furthermore, low functioning patients might not be able to grab the devices or open their hands to grip the trackers.

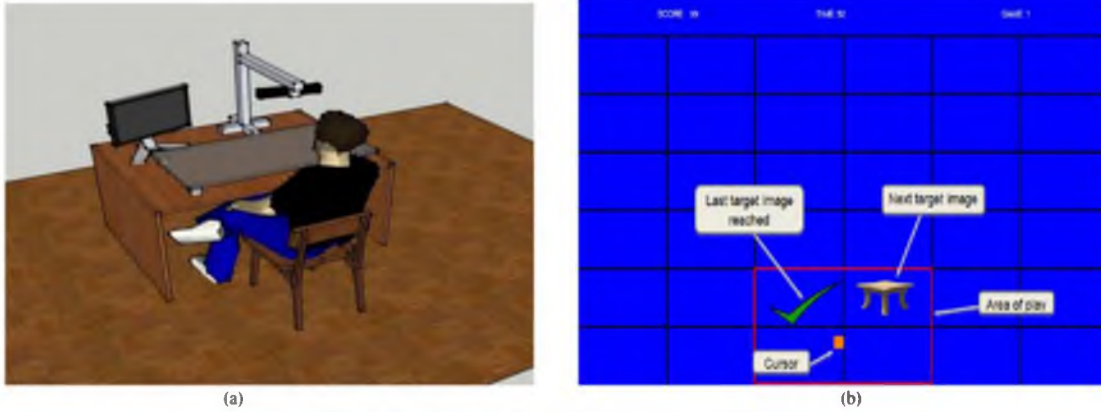


Fig. 1. (a) Illustration of the system's setup; (b) Annotated screenshot of the game.

Microsoft Kinect [21] is another low-cost tracker that recently became available. It constitutes a good tracking option for a home-based rehabilitation systems due to its low cost and its reasonably high accuracy (xy resolution: 3mm, z resolution: 10 mm [22]). Schönauer et al. [9] compared the tracking capabilities of this device with a high-end motion capture system. Their study concluded that even though Kinect cannot measure as many parameters and has a lower accuracy, most of the games they developed could be played using either tracker.

Different uses for Kinect have been explored since it became available. It has been used to improve the measurements of inertial sensor [23] and wearable haptic devices [24]. It has also been used to estimate the pose of the lower-limbs of a person using a wheeled walker [25]. In the field of rehabilitation, Kinect was used to track the user's upper body in a game designed to treat balance issues [26]. In order for Kinect to find where the person is standing and start tracking the body, users need to stand about two meters from the device with their arms above their head and maintain this position for a couple of seconds. Most stroke patients cannot get to this position or stay still for the time required, making this calibration method inappropriate for these patients.

Home-based rehabilitation can become a reality using new and affordable technology such as Kinect. The system presented here uses this device to track the patient's hand to play a game designed specifically for upper body rehabilitation of stroke survivors. The calibration process is easy and only requires the patients to move their hands in a waving motion on a flat surface at table height.

Our recent work [27] demonstrated the feasibility of the system with one stroke survivor. The high acceptability of the system motivated a new study to be performed with a small group of cohesive subjects, all of whom have a Fugl-Meyer score above 33. The system presented here uses Kinect to track the patient's hand to play a game designed specifically for upper body rehabilitation of stroke survivors. The calibration process is easy and only requires the patients to move their hands in a waving motion on a flat surface at table height. Furthermore, no extra accessories, such as markers or

hand supports, are required.

The remaining of the paper is organized as follows: a description of the system and the study are found on Section II; the results of the study and a discussion are presented on Sections III and IV; finally, section V describes the conclusions.

## II. METHOD

### A. Hardware Setup

A schematic of the systems' setup is shown in Fig. 1 (a). In order to play the game, the patient sits in front of a table with a monitor, a hand support and a stand for the Kinect. A Dell Inspiron M501R Dual-Core processor and 3GB memory laptop was used to run the software. The game was displayed on a 20" monitor, and to play it, subjects move their arm resting on the support. Table 1 shows the cost of the components of this prototype system.

The hand support is required because the patients' general lack of strength makes it impossible for them to keep their arms raised for long periods of time. A transparent surface was used so the hand could be tracked, because the Kinect cannot track the hand while in contact with an opaque surface, as described in [27].

TABLE I  
LIST OF THE COMPONENTS OF THE SYSTEM AND THEIR COST

Description	Cost
Kinect	\$150
Hand support	\$70
Stand for Kinect	\$320
Computer	\$450
Monitor	\$130
Table	\$50
Total	\$1170

### B. Accuracy of Kinect

A small study was performed to determine the accuracy of the Kinect. A marker (a 5x15 cm piece of white cardboard) was placed in different locations on top of the hand support (xy plane) and above it (z axis). The real value was measured with a ruler and compared with the real world coordinates

measured by Kinect. The coordinate system used by Kinect has its origin in the center of the device with the x- and y-axes coplanar with it and the z-axis along the camera axis. For the accuracy study, the marker was first placed at -30 cm on the x-axis. Measurements were taken every 5 cm along the x-axis until the marker reached 20 cm on the x-axis (the Kinect was mounted slightly off-center of the transparent surface). This procedure was repeated five times and all measurements were taken with the marker resting on the hand support ( $z=71$  cm) and at  $y=-15$  cm. The same procedure was done for the y axis with the marker first placed on -15 cm and moved 5 cm at a time until it reached 20 cm. In this case, all measurements were taken at  $x=-30$  cm and  $z=71$  cm. For the z axis, measurements were taken every 5 cm from  $z=51$  cm to  $z=71$  cm while the marker stayed at (0,0) in the xy plane.

### C. Software Setup

#### 1) Interaction with Kinect

Data was obtained using an open source driver made available by PrimeSense [28], the company who developed Kinect. Tracking of the hand was performed using NITE, a motion tracking middleware developed by Open Natural Interaction (OpenNI) [29]. The location of the hand was available as real world coordinates and as projective coordinates (real world x and y coordinates mapped to image pixels).

A Kalman filter [30] was implemented to decrease jitter and noise from the data. The Kalman filter combined the measured position with an estimated position to reduce the noise. The filter was implemented using functions from an OpenCV library [31]. A transition and a measurement matrix, and values for process noise, measurement noise and error are customizable according to the system's characteristics. The measurement matrix was formed with the position data measured by the Kinect and the transition matrix was initially implemented based on the linearized equations of motion (using the Taylor series terms up to second order), assuming a particle moving in a straight line with constant acceleration. These equations are shown below:

$$p(t+1) = p(t) + v(t)\Delta t + a(t)\frac{\Delta t^2}{2} \quad (1)$$

$$v(t+1) = v(t) + a(t)\Delta t \quad (2)$$

$$a(t+1) = a(t) \quad (3)$$

Where  $a$  is acceleration,  $v$  velocity,  $p$  position and  $\Delta t$  is the time interval. Assuming  $\Delta t=1$ , and writing the equations in matrix form, the following is obtained:

$$\begin{bmatrix} p(t+1) \\ v(t+1) \\ a(t+1) \end{bmatrix} = \begin{bmatrix} 1 & 1 & 0.5 \\ 0 & 1 & 1 \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} p(t) \\ v(t) \\ a(t) \end{bmatrix} \quad (4)$$

The transition matrix (A) for movement in a two-dimensional space can be inferred from (4):

$$A = \begin{bmatrix} 1 & 0 & 1 & 0 & 0.5 & 0 \\ 0 & 1 & 0 & 1 & 0 & 0.5 \\ 0 & 0 & 1 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 & 0 & 1 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} \quad (5)$$

Several values and different models for the transition matrix were tested until the filter was tuned to minimize jitter with no observable lag. Values in the posteriori error estimate covariance matrix were set to 0.1, values in the process noise covariance matrix (Q) were set to 0.001 and values in the measurement noise covariance (R) were set to 0.1. The transition matrix that gave the best results is shown below:

$$A = \begin{bmatrix} 1 & 0 & 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 & 0 & 1 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} \quad (6)$$

#### 2) Game Design:

A game was designed and developed specifically for upper limb rehabilitation of stroke survivors. The game fulfills requirements developed in conjunction with the physical therapist team at the University of Utah's Rehabilitation and Wellness Clinic. Specifically, the long-term objective of this type of game-based upper limb rehabilitation is to increase range of motion and decrease spasticity.

The game requires the patients to control a cursor on the screen by moving their hand. The goal of the game is to select images that randomly appear in any cell of a 6X6 grid. To select an image, patients need to locate the cursor inside the appropriate cell. Fig. 1(b) shows an annotated screen shot of the game and Fig. 2 shows a picture of a patient playing the game. A more complete description of the game can be found in [27].

The game and the system were designed aiming to fulfill the following design patterns described by Goude et al. [32]. These patterns were also used by Burke et al. for the design of their games for stroke rehabilitation [7].

- Right level of difficulty: The game should be difficult enough to keep the user entertained and be therapeutical without causing any harm or pain. This was achieved by personalizing the game to the patients' skills. The amount of motion required and the time available to catch the next image varies for each patient.

- Quick games: Movement of the impaired arm requires big efforts from the stroke survivor. Games have to be quick to avoid exhausting the patient. The game has a total of 10 rounds and each one lasts between one and two minutes and there is a break of half the length of the round between them. The entire game lasted from 20 to 35 minutes.

- Direct feedback: It is important that the game provides feedback to the users so they understand the consequence of their actions. In this case, a cursor in the screen moved as the hand moved and a check mark was shown when the image was reached. Also, knowing the score achieved in the game

motivates the patient to improve. The score was shown during each round, during the break and at the end of the game.

- **Precise maneuvering:** Users should not be able to fool the system (e.g. getting the same results from small wrist movements instead of swinging the arm) and increase their score by doing so. This game tracks the location of the hand forcing the user to move the entire arm to reach the desired location.

In order to make the systems suitable for the home environment, the following features were also taken into account while designing the system:

- **Easy to configure:** Users without any previous knowledge of computer software should be able to run the game and start playing. This game does not require any configuration. After running the software simple instructions are given in order for the system to get calibrated and start playing it.

- **Work at home:** The system should not require big spaces or any special condition not found in the home environment. These conditions are met by the system proposed.

- **Low cost:** The system should be affordable so patients can buy it or rent it and use it at home. The total cost of this prototype system is 1170 USD.

- **Minimal therapist involvement:** The system was designed for home-based rehabilitation so minimal or no therapist involvement is required.

#### D. Human Study

A study was implemented to evaluate the acceptance of the system and investigate the efficacy. This study was approved by the University of Utah's Institutional Review Board (study number 00053748). The study was carried out with five stroke survivors (3 female,  $71.6 \pm 7.4$  years old,  $57.2 \pm 16.3$  months post-stroke) and five control subjects (3 female,  $65.2 \pm 5.2$  years old). Three of the stroke survivors played the game once a day for ten consecutive weekdays (Monday through Friday). The other patients could not attend all the sessions due to difficulty in commuting to the clinic. They played the game three times a week (Monday, Wednesday and Friday), for two weeks, a total of 6 sessions. A pre-test was performed to obtain patient's range of motion and teach the user how to play the game. Teaching the patient how to play the game before the study begins is intended to decrease score improvement due to game learning. Sessions were 20 minutes long at the beginning of the study and their length increased each day, reaching 35 minutes by the last day. Further discussion of the duration of each game can be found in [27].

The Fugl Meyer is a stroke-specific, performance based impairment measure and provides information on motor recovery [33]. For those patients who participated on ten sessions, Fugl Meyer upper extremity motor score was obtained before and after the study to determine if any improvement was achieved. Preliminary analysis of this data suggested that any improvement in six sessions was likely to be statistically insignificant. Therefore, this test was only performed to this group of patients to determine if they met the study's inclusion criteria.

Patients also answered surveys before and after the study in order to analyze their expectations about and the acceptability of the system. Control subjects played the game one time.

Their range of motion and scores were saved and compared with the results obtained by the stroke survivors. Testing the control subjects also had the purpose of determining if the game was comfortable to play and easy to understand.

Stroke survivors were recruited through the University of Utah's Rehabilitation and Wellness clinic. The inclusion criteria for the subjects were: 1) individuals with unilateral stroke, distribution of right or left middle cerebral artery ischemic lesion, 2) at least 9 months post-stroke to prevent any recovery occurring due to spontaneous recovery [34], 3) present with "higher" level functional ability of the upper extremity defined by the Fugl Meyer upper extremity motor score as greater than 33 out of 66 [35], 4) age over 40 years of age, 5) no uncorrected vision loss. Control subjects had to meet inclusion criteria 4) and 5).

#### E. System's Calibration

The system needs to be calibrated before playing the game. This process consists of two simple steps. First, users have to move their arm on the transparent surface in a waving motion for about 5 seconds until the system recognizes the arm and starts tracking it. This constitutes a simple task and all patients were able to complete it without any difficulty. Furthermore, if the system would be used by a lower functioning patient not able to complete this motion, tracking can be started by another person who would then remove his/her arm from the support to allow the patient places his/her arm. For the second step, users are asked to move their arm as far as they can to the right, left, away from their body and toward their body. This way, the user's range of motion is found and it is used during the game so patients are not required to move their arm further than what they can. Fig. 3 shows the calibration screen with sample data from a stroke patient.

#### F. Data Analysis

The patient's game score per minute was used to analyze the performance of the system. These values were obtained by dividing the total score of each day by the duration (in minutes) of the game on that day. The score was equal to the total number of images the user reached during the session.

The surveys had statements about the acceptability of the system and a line under each one. The left end of the line represented a "strongly disagree" feeling about the statement and the right end a "strongly agree" feeling. Patients were asked to make a mark on the location of the line that best described how they felt about the statement. To analyze these data, the location of the mark was measured with a ruler and transformed to a percentage.

The statistical analysis of the data (e.g. ANOVA studies) was done using Stata 11 statistical software [36]. P values under 0.05 were considered statistically significant.

### III. RESULTS

#### A. Accuracy Study of Kinect

Fig. 4 (a), (b) and (c) show the results obtained in Kinect's accuracy study. The average error was  $-0.8 \pm 2.3$  mm on the x





Fig. 2. Stroke survivor playing the game



Move your hand as far as you can on every direction

Fig 3. Screen shot of the range of motion calibration screen

axis,  $0.6 \pm 1$  mm on the y axis and  $5.9 \pm 6$  mm on the z axis.

#### B. Control Subjects

Results obtained by the control subjects are shown on Table II.

TABLE II  
CONTROL SUBJECTS' RESULTS

Subject	Score first try (score/min)
1	74.1
2	76.4
3	85.3
4	89.8
5	84.2
Mean ( $\pm$ S.D.)	$81.9 \pm 6.5$

#### C. Stroke Survivors

Table III shows the difference between the pre-test score and the scores obtained on the first and last days of the study. Table IV shows stroke survivors' game and Fugl-Meyer scores. Differences in Fugl-Meyer scores are also shown. Fig. 5 shows the subjects' game scores obtained during the study.

TABLE III  
STROKE SURVIVORS' GAME AND FUGL-MEYER SCORES

Subject	Score difference from pre-test to first day	Score difference from pre-test to last day	Fugl-Meyer Score change
1	2.03	38.19	-2
2	6.80	22.20	6
3	13.42	18.52	1
4	4.17	12.07	n/a
5	3.98	14.15	n/a
Mean ( $\pm$ S.D.)	$6.08 \pm 4.44$	$21.03 \pm 10.36$	
P value		0.018	

#### D. Surveys

The averaged results from the pre-study and post-study surveys are shown in Table V. The value indicates in what percentage the subjects agreed with each statements. The P values from the ANOVA test are also shown.

### IV. DISCUSSION

The accuracy study performed with Kinect shows that this inexpensive device that be used to control a game in a home-based rehabilitation system. The results are in agreement with [22].

Patients liked the fact that they did not need to grab anything with their hands to play the game. Furthermore, the calibration process was simple and easy for patients to understand. The accuracy and precision of the device were sufficient for the movements made by the patients during the game (typical displacements of required to move the cursor from the center of a cell to the center of an adjacent cell were 87 mm in the x-axis and 61 mm in the y-axis).

Control subjects felt comfortable playing the game. However, the game was not challenging or very entertaining for them. The scores they obtained were higher than the scores obtained by the stroke survivors the first time they played the game, with a statistically significant difference ( $p=0.000$ ).

Surveys show the system had a high acceptability from stroke survivors. They felt playing the game could improve arm mobility and that computer game based therapy is more enjoyable than classical therapy. Patients also found the game easy to understand and were willing to use the system at home. There were no big changes in patient's Fugl Meyer score with one exception: Subject 2's score increased from 45 to 51. Before the study, this patient was not using his impaired arm in his daily activities. Playing the game everyday forced the subject to move the arm, improving its mobility. The other two subjects used their impaired arms more frequently in daily life. This highlights the clinical need for accessible and enjoyable therapy.

All patients improved their game scores. There was a statistically significant difference between the increase of the score from pre-test to day one and the increase from pre-test to last day ( $p=0.018$ ). Thus, playing the game had a positive effect on the patients versus not playing it. It was also found that patients who attended ten sessions had a higher mean score increase at the end of the study than those who played it for six times (26.3 vs. 13.1).

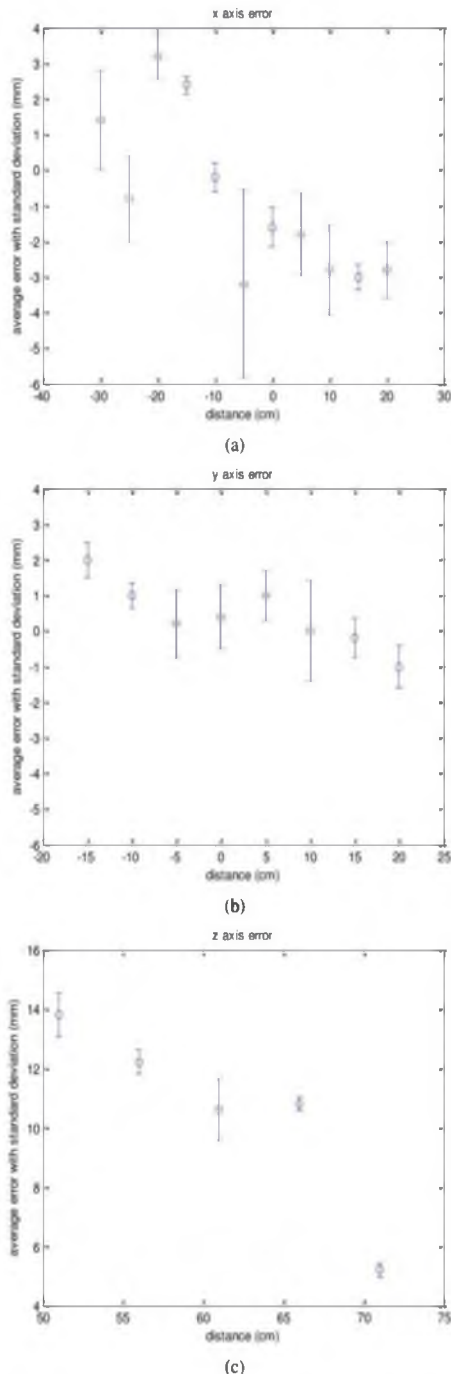


Fig 4. Results for accuracy study of Kinect: (a) x axis error; (b) y axis error; (c) z axis error.

Some of the patients had trouble sliding their hand on the transparent support and a pillow case was used to wrap their arms and decrease friction. A hand support build with lower friction materials could add more comfort to the gaming experience.

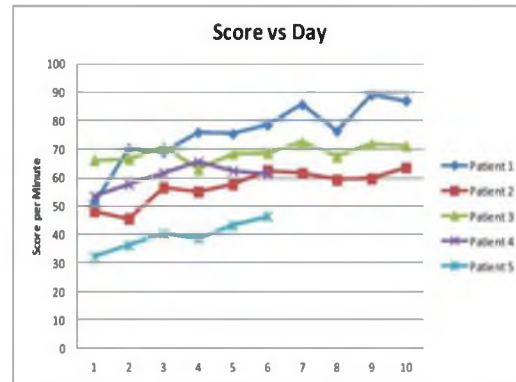


Fig 5. Patients' scores through the study

The features considered during the system designed were ranked by this paper's author and co-authors. The final result, starting by the most important feature, is shown below:

1. Right level of difficulty
2. Direct feedback
3. Easy to configure
4. Low cost
5. Minimal therapist involvement
6. Precise maneuvering
7. Quick games

The survey results showed that "easy to understand" had 87% agreement suggesting that Feature 1 (right level of difficulty) was met. The system provided direct feedback and is easy to configure. The prototype cost approximately \$1000 with several components that could be less expensive in a commercial device. The game did not have any therapist involvement. The device provided the necessary resolution to allow precise maneuvering. Ten rounds were played in a single game, taking at most 35 minutes, with time for calibration included.

It was difficult to enroll patients on the study. Even though many were interested on participating, difficulty with commuting to the clinic kept them from enrolling. This problem shows the need of a rehabilitation system suitable for use at the home environment.

The need to use the plastic hand support constitutes a potential drawback to the system since it increases its cost, is not commercially available and some of the patients had trouble sliding their arms on in. These issues will be addressed in future versions of the system.

Future work on the system includes another study including lower-functioning and younger subjects. The new study would be longer (3x/week for 4 weeks) and performed with subjects that would receive more benefit from this type of intervention (9 months to 1 year post-stroke). Games that address cognitive rehabilitation and games that integrate rehabilitation and art (e.g. photography and music) will also be tested. Changes in the infrastructure could also be made. A bigger playing area (hand support) and an adjustable height table would increase the users' comfort.

TABLE IV  
INFORMATION AND RESULTS OF STROKE SURVIVORS

Subject	Hemisphere of brain affected by stroke	Score per minute first try (pre-test)	Score per minute first day of study	Score last day of study	Pre-study Fugl-Meyer Score	Post-study Fugl-Meyer Score
1	Right	48.9	51.0	87.1	53	51
2	Right	41.4	48.2	63.6	45	51
3	Right	52.7	66.2	71.3	38	39
4	Right	49.3	53.5	61.4	49	n/a
5	Left	32.3	36.3	46.45	46	n/a
Mean ( $\pm$ S.D)		44.9 $\pm$ 8.2	51.0 $\pm$ 10.7	65.9 $\pm$ 14.8		

TABLE V  
RESULTS FROM SURVEYS

Survey Question	Pre-study	Post-study	P value
Computer game based therapy can improve arm mobility	82.4	85.0	0.82
Computer game based therapy is more enjoyable than classical therapy	75.3	84.3	0.43
It will be comfortable to play a computer game for therapy	78.4	72.6	0.67
The computer game for therapy will be easy to understand	87.1	87.3	0.97
I would be willing to use the system at home every day	n/a	85.1	n/a

## V. CONCLUSION

The system proposed showed promising results. Patients enjoyed using it and some improvement in arm movement was observed. The infrastructure used for this game can be used to test new games and their outcome for arm rehabilitation. Further studies are going to be carried with more complex and entertaining games.

## ACKNOWLEDGMENT

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## **CHAPTER 5**

### **CONCLUSION AND FUTURE WORK**

#### **5.1 Conclusions**

This thesis described the design, developing and human testing of a rehabilitation system for the impaired upper limb of stroke survivors using computer games and the Kinect. A computer game was designed and written specifically for the rehabilitation of stroke survivors. Additionally, infrastructure that can be used for future developments was built and tested.

A human study was performed in order to test the following hypothesis: Upper limb rehabilitation of stroke survivors, using computer games and Kinect, will:

- maintain or improve patient's mobility, and
- be more enjoyable than conventional therapy.

Patient's Fugl-Meyer upper extremity motor scores were used to investigate the first part of the hypothesis. There were no big changes in patients' scores with one exception: one of the subject's score improved by six points; confirming that therapy with the system maintains or improves patient's mobility. Usability surveys were used to determine if patients enjoyed this kind of therapy more than conventional therapy. Subjects were asked if they agreed with the following statement: "Computer game based therapy is more enjoyable than

classical therapy". The average response was that patients agreed with the statement in  $84.4 \pm 16.5 \%$ .

The system fulfilled the seven features considered during the design process. Each feature is discussed below:

1. *Right level of difficulty*: All patients were able to play the game and improve their scores over the study. Furthermore, none of the patients felt extremely tired after a session.
2. *Direct feedback*: The game score was displayed at all times and users were able to see it and comment about it. Patients remembered the score from the previous day and tried to improve it.  
  
Patients quickly understood that moving their arm caused the cursor on the screen to move and were also able to control it.
3. *Easy to configure*: No configuration was required to play the game. Before playing the game, only tracking of the hand had to be started and the range of motion calibrated. Both processes were completed by stroke survivor without any difficulty.
4. *Low cost*: The total cost of this prototype system was 1170 USD and it can be decreased in future and commercial versions.
5. *Minimal therapist involvement*: There was no need for a therapist to be present during the study. Only one person was with the patient during the sessions and the only tasks performed were helping the patient sit down in the right place and start the game.

6. *Precise maneuvering*: The game required the patients to move the impaired arm and it was not possible to fool the system and perform smaller motions (e.g. twisting the wrist) to obtain the same results. However, when the game was played in only four squares patients could keep the cursor close to the intersection of the squares and perform small motions to catch the new image.
7. *Quick games*: The total length of the game was between 15 and 30 minutes with each round being 1 to 2 minutes long. None of the patients were exhausted at the end of the sessions

The system was implemented using a hand tuned Kalman filter. However, later tests showed that implementing the filter using the equations of motion and the results from Kinect's accuracy study yields better results. A comparison between the two implementations can be found in the appendix.

## 5.2 Future work

Promising results were obtained from the system but there are some aspects that can be further studied or improved. Future work on the system includes a longer study (e.g, 3 times per week for 4 weeks) including younger and lower-functioning subjects. For this new study, stroke patients that would receive a bigger benefit from this type of intervention (9 months to 1 year poststroke) would be recruited. Four weeks and longer studies are common for this kind of systems [1-3].

Regarding the software of the system, games addressing cognitive rehabilitation will be designed and tested. The integration of art, such as photography and music, and rehabilitation will be included in future games.

The infrastructure of the system will also be modified to increase patient's comfort while playing the game. These changes include a bigger playing area and an adjustable height table.

### 5.3 References

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## **APENDIX A**

### **KALMAN FILTER COMPARISON**

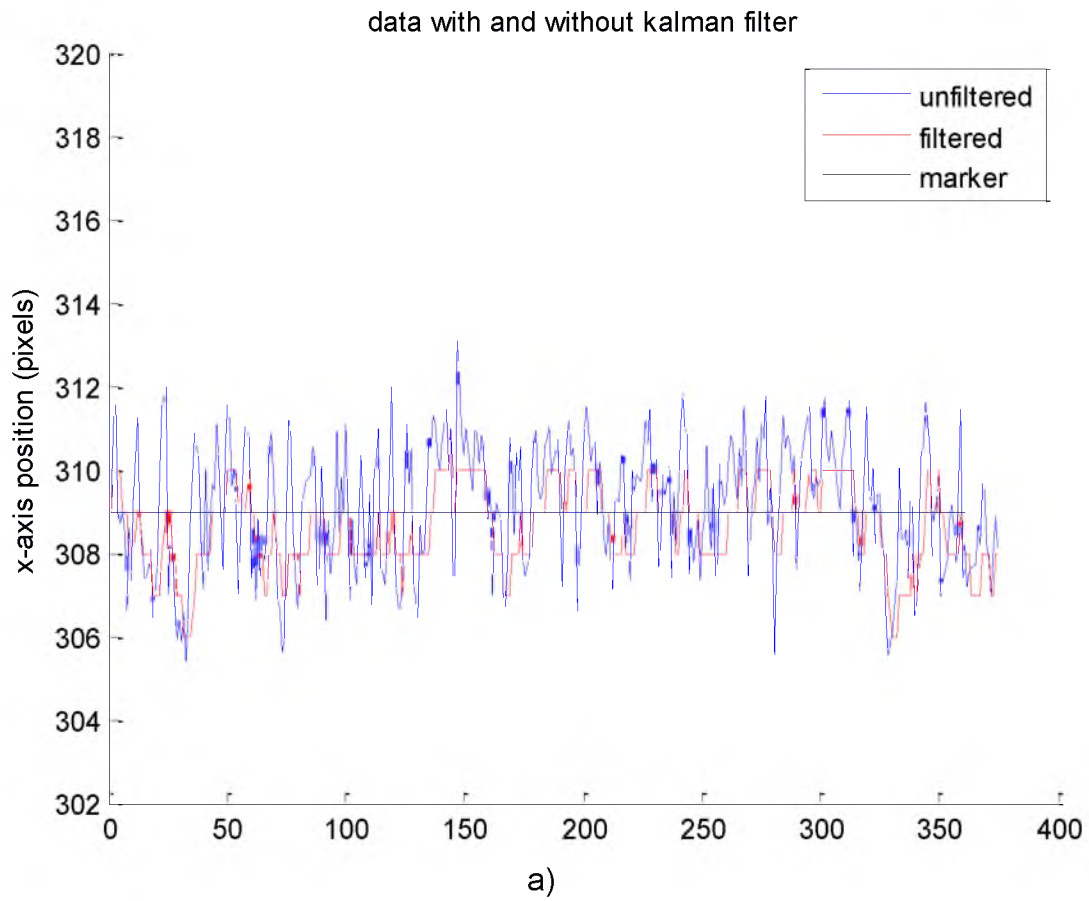
Data from two implementations of the Kalman filter are shown below. The filters were implemented and tested using the infrastructure developed for the stroke rehabilitation system. A marker was tracked by Kinect and filtered and unfiltered data was recorded while the marker was kept in the same location. Different transition matrixes and configuration parameters where used on each filter. One filter uses the equations of motion in the transition matrix while the other was hand tuned and the matrix was modified until the desired results were obtained. The filter using the equations of motion also uses the results from Kinect's accuracy study as the measurement error.

#### **A.1 Equations of motion-based Kalman filter**

The filter was implemented using the transition matrix and configuration parameters shown in Table A.1. Figures A.1 a) and b) show the output data using the filter.

Table A.1. Equations of motion-based Filter Parameters

Parameter	Value
Transition Matrix	$A = \begin{bmatrix} 1 & 0 & 1 & 0 & 0.5 & 0 \\ 0 & 1 & 0 & 1 & 0 & 0.5 \\ 0 & 0 & 1 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 & 0 & 1 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}$
Posterior error estimate	0.01
Process noise	0.00001
Measurement noise	1



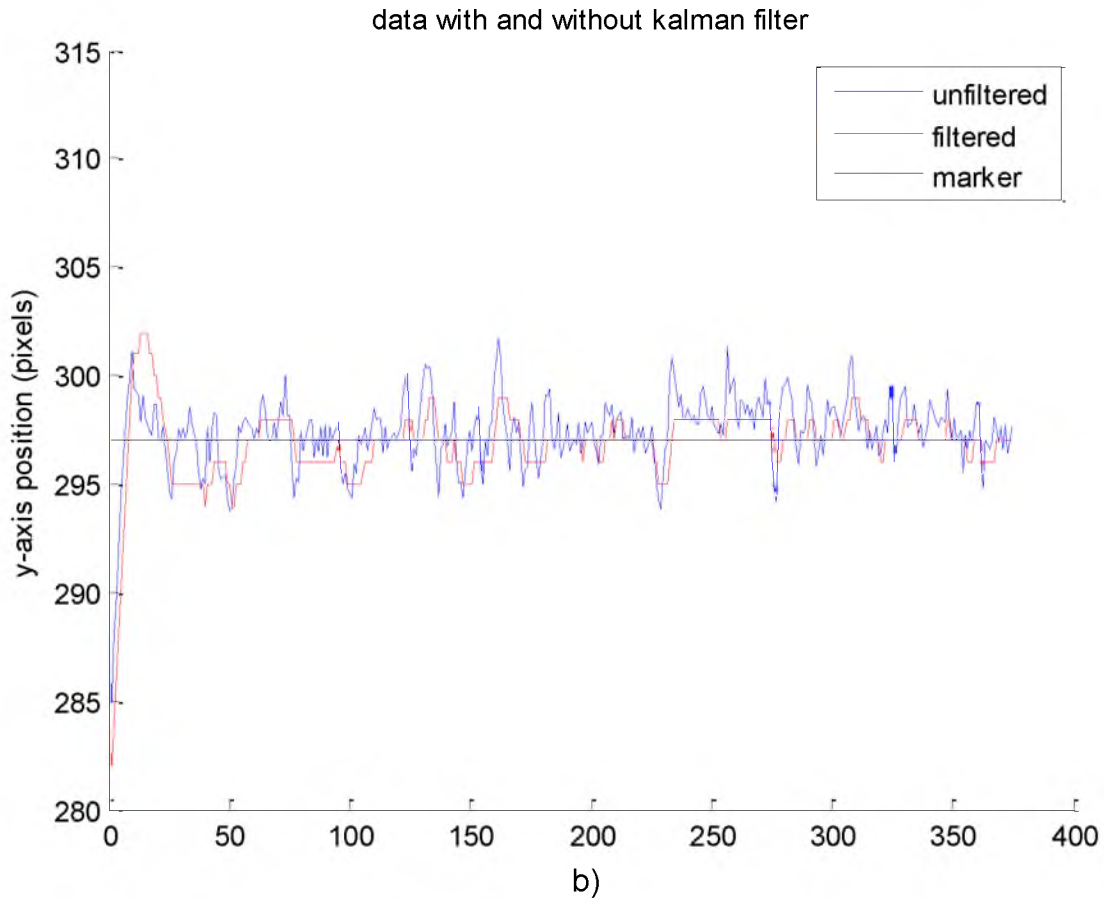


Figure A.1. Filtered and unfiltered data using equations of motion based

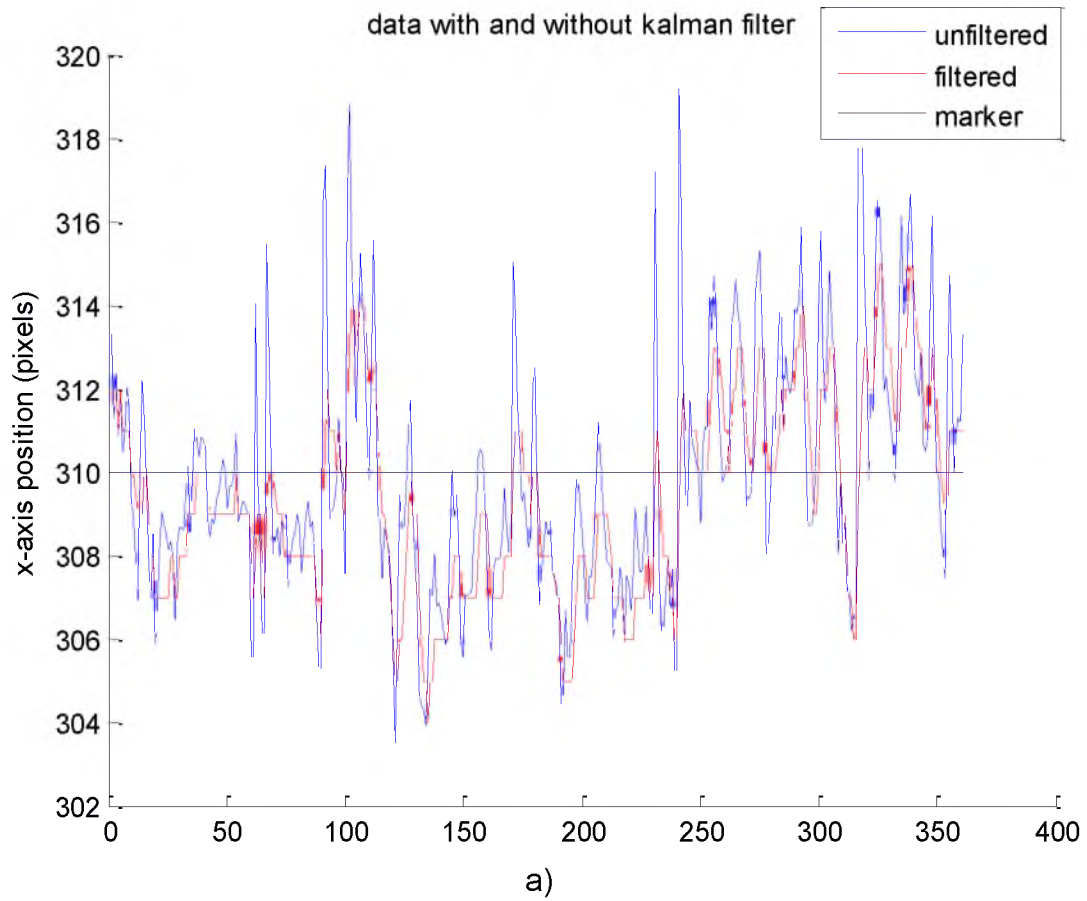
Kalman filter. a) x-axis data, b) y-axis data.

## A.2 Hand-tuned Kalman filter

The hand-tuned Kalman filter was implemented for the patient study. The parameters used in this filter are listed in Table A.2. Figures A.2 a) and b) show the output data with and without the filter for the x- and y- axes.

Table A.2. Hand-tuned Filter Parameters

Parameter	Value
Transition Matrix	$A = \begin{bmatrix} 1 & 0 & 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 & 0 & 1 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}$
Posterior error estimate	0.1
Process noise	0.001
Measurement noise	0.1



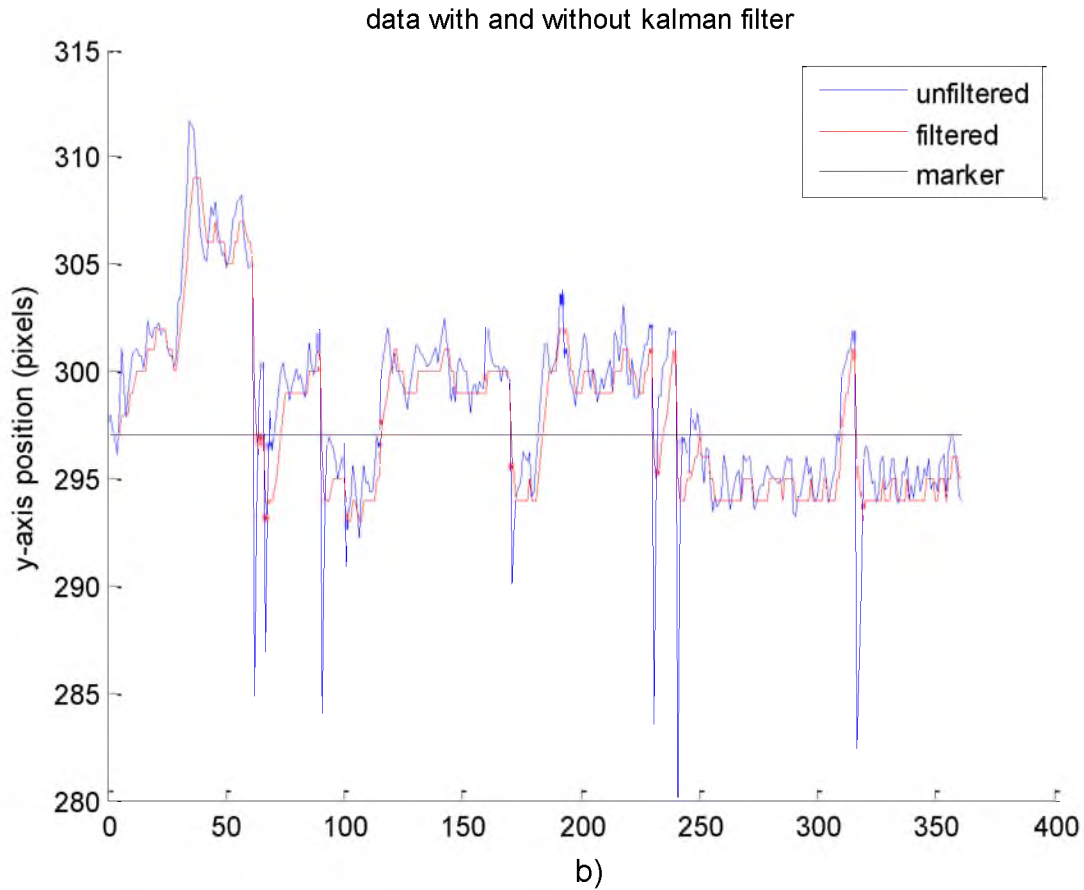


Figure A.2. Filtered and unfiltered data using a hand tuned Kalman filter.

a) x-axis data, b) y-axis data.

### A.3 Summary

The graphs in Figures A.1 and A.2 show that both implementations decrease jitter by eliminating noisy points. Errors for all data sets are shown in Table A.3.

The filter using the equations of motion and the results from Kinect's accuracy study gives a smoother output as evidenced by the data in Table A.3.

Therefore, an implementation based on equations of motion should be used for future work. Because human motion in healthy subjects has been identified to minimize jerk, this aspect should be investigated for the next implementation.

Table A.3 Errors

<b>Data</b>	<b>X-error, pixels (Mean <math>\pm</math> S.D.)</b>	<b>Y-error, pixels (Mean <math>\pm</math> S.D.)</b>
Unfiltered	0.53 $\pm$ 2.35	0.84 $\pm$ 3.23
Filtered with Equations of Motion	-0.34 $\pm$ 0.99	-0.16 $\pm$ 1.83
Filtered with Hand-Tuned Filter Used in Study	0.45 $\pm$ 2.34	0.86 $\pm$ 3.6